

C II ABUNDANCES IN EARLY-TYPE STARS: SOLUTION TO A NOTORIOUS NON-LTE PROBLEM

M. F. NIEVA

Dr. Remeis Sternwarte Bamberg, Sternwartstr. 7, D-96049 Bamberg, Germany and
 Observatório Nacional, Rua General José Cristino 77 CEP 20921-400, Rio de Janeiro, Brazil

AND

N. PRZYBILLA

Dr. Remeis Sternwarte Bamberg, Sternwartstr. 7, D-96049 Bamberg, Germany
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ABSTRACT

We address a long-standing discrepancy between non-LTE analyses of the prominent C II $\lambda\lambda 4267$ and $6578/82 \text{ \AA}$ multiplets in early-type stars. A comprehensive non-LTE model atom of C II is constructed based on critically selected atomic data. This model atom is used for an abundance study of six apparently slow-rotating main-sequence and giant early B-type stars. High-resolution and high-S/N spectra allow us to derive highly consistent abundances not only from the classical features but also from up to 18 further C II lines in the visual – including two so far unreported emission features equally well reproduced in non-LTE. These results require the stellar atmospheric parameters to be determined with care. A homogeneous (slightly) sub-solar present-day carbon abundance from young stars in the solar vicinity (in associations and in the field) of $\log C/H + 12 = 8.29 \pm 0.03$ is indicated.

Subject headings: line: formation - radiative transfer – stars: abundances, early type

1. INTRODUCTION

One of the most abundant metals in the universe is carbon, the central building block of all organic chemistry. Abundances derived from luminous early B- and late O-type stars provide important constraints on stellar and galacticochemical evolution. In extragalactic applications (e.g. analyses of dwarf stars in the Magellanic Clouds, see e.g. Hunter et al. 2005; Korn et al. 2005) one desires to study the *strongest* features in the metal line spectra, as these are the only measurable at low S/N and/or high projected rotational velocities. In the case of ionized carbon these are the prominent lines of the two multiplets C II $\lambda\lambda 4267.02/4267.27 \text{ \AA}$ and $6578.03/6582.85 \text{ \AA}$. These lines are unfortunately highly sensitive to non-LTE effects, as well as to the choice of stellar atmospheric parameters. So far, all studies from the literature failed to derive consistent abundances from these lines.

The problem was addressed by Lennon (1983), Eber & Butler (1988) and Sigut (1996: S96) using C II model atoms of increasing complexity. Spectrum synthesis based on the latter two non-LTE model atoms obtained better – but apparently still not good – agreement with observation when compared to earlier work or LTE results. Non-LTE abundance analyses in Galactic OB stars e.g. by Gies & Lambert (1992) and Kilian (1992) employing the Eber & Butler (1988) model derived a metal deficiency (including C) in these young stars with respect to the Sun, in accordance with studies of H II regions.

The present work aims at providing a solution to the classical non-LTE problem of carbon abundance determinations in OB stars. A reliable C II model atom is developed and first applications on high-quality spectra are presented. Besides great care in the selection of atomic data, special emphasis is also given to an accurate atmospheric parameter determination, both in order to mini-

mize systematic uncertainties. The measurable C II spectrum in the visual is investigated, the two prominent line multiplets as well as numerous weaker lines.

2. MODEL CALCULATIONS

A hybrid approach is used for the non-LTE line formation computations. These are based on line-blanketed LTE model atmospheres calculated with ATLAS9 (Kurucz 1993). Synthetic spectra are computed with recent versions of DETAIL and SURFACE (Giddings 1981; Butler & Giddings 1985), solving the restricted non-LTE problem – see Przybilla et al. (2001) for details.

Hydrogen and He I/II populations are computed using recent model atoms by Przybilla & Butler (2004) and Przybilla (2005), respectively. We have compared our synthetic H and He I/II lines with predictions from Lanz & Hubeny (2003) in the effective temperature range of $27500 \text{ K} \leq T_{\text{eff}} \leq 32500 \text{ K}$ for dwarf as well as giant stars. Overall good agreement is found. Exceptions are the He I singlet lines, which are predicted (significantly) stronger in our approach, in accordance with observation.

The C II model atom considers LS-terms up to principal quantum number $n=10$ and angular momentum $\ell=9$ explicitly in non-LTE, with all fine-structure sub-levels combined into one. The doublet and quartet spin-systems are treated simultaneously. Level energies are adopted from Moore (1993), S96 and Quinet (1998).

Oscillator strengths from three sources are considered: fine-structure data from *ab-initio* computations using the multiconfiguration Hartree-Fock method in the Breit-Pauli approximation (Froese Fischer & Tachiev 2004: FFT04), data from an application of the Breit-Pauli R-matrix method (Nahar 2002a) and results obtained in the Opacity Project (OP) from a close-coupling method in the LS-approximation (Yan, Taylor & Seaton 1987). Our primary source of *gf*-values is FFT04, followed by OP and Nahar for the remaining transitions. Note that data for several important transitions from Nahar dis-

agree with those from FFT04 and OP, which show consistency among each other. Intercombinations are neglected because of the very small gf -values and high densities.

Photoionization cross-sections are taken from the OP (Yan & Seaton 1987) where available. For the remainder, data from Nahar (2002b) are adopted. The choice is empirically motivated, giving preference to the OP data in order to reproduce observation over the entire parameter range simultaneously from all indicators. The two data sets show differences in the resonance structures.

Effective collision strengths for electron impact excitation among the lowest 16 LS-states are adopted from R-matrix computations of Wilson, Bell & Hudson (2005). Collisional excitation for transitions without reliable data are treated using the Van Regemorter (1962) approximation in the optically allowed case and via the semi-empirical Allen (1973) formula otherwise. Collision strengths varying between 0.01 ($\Delta n \geq 4$) to 100 ($\Delta n = 0$) are employed, as suggested by evaluation of the detailed data of Wilson et al. (2005).

Collisional ionization rates are evaluated according to the Seaton (1962) approximation, with threshold photoionization cross-sections from OP and Nahar (2002b), allowing for an empirical correction of one order of magnitude higher for the $6f^2F^\circ$ and $6g^2G$ terms – corresponding to the upper levels of the C II $\lambda\lambda 6151$ and 6462 \AA transitions. For completeness, a C III model atom is also accounted for in the computations, but its details are of no further importance to the present study.

Voigt profiles are adopted in the formal solution using SURFACE. Wavelengths and gf -values are taken from Wiese et al. (1996). Radiative damping parameters are calculated from OP lifetimes and coefficients for collisional broadening by electron impact are adopted from Griem (1974) for the C II $\lambda 4267 \text{ \AA}$ doublet, while the approximation of Cowley (1971) is used for the other lines.

3. ANALYSIS

Six apparently slow-rotating stars are considered for the model atom calibration and first applications. The observations consist of high-resolution, high-S/N spectra with wide wavelength coverage, obtained with FEROS at the 2.2m telescope at ESO (La Silla, Chile).

Effective temperatures T_{eff} are derived spectrophotometrically from IUE fluxes and Johnson and 2MASS magnitudes for all the stars except HR 2928 where T_{eff} is in agreement with Kilian (1992). Further constraints can be derived from the He I/II ionization equilibrium for τ Sco and HR 3055. Figure 1 displays best fits to the spectrophotometry. Gravities $\log g$ are derived from line profile fits to $H\delta$, $H\beta$, $H\gamma$ and $H\alpha$. Examples for some H and He I/II lines in τ Sco and HR 5285 are given in Fig. 2.

After constraining T_{eff} and $\log g$ we compute small grids of synthetic spectra for different carbon abundance $\varepsilon(C) = \log(N_C/N_H) + 12$ and several values of microturbulence ξ . These grids are used for C abundance determinations from observation via a χ^2 -minimization technique. The free fitting parameters are $\varepsilon(C)$, $v \sin i$ and macroturbulence ζ . The macroturbulent velocities in the sample stars remain smaller than twice the sound speed. The microturbulent velocity is fixed in the usual approach, by demanding $\varepsilon(C)$ to be independent of the equivalent width W_λ of the C II line ensemble (see Fig. 5).

An excellent match between theory and ob-

servation is achieved, as shown in Fig. 3 exemplarily for the hottest (τ Sco) and coolest (HR 5285) star in our sample. The complete linelist includes the C II $\lambda\lambda 3919.0/20.6$, $4267.0/.2$, $5133.3/37.3/39.2/43.4/45.2/51.1$, $5648.1/62.5$, 6151.5 , 6461.9 , $6578.0/82.9$, $6779.9/80.6/83.1/87.2/6791.5$ and 6800.7 \AA transitions. Fits to C II $\lambda 6462 \text{ \AA}$ for all the stars are shown in Fig. 4. This line together with C II $\lambda 6151 \text{ \AA}$ is subject to marked non-LTE effects, turning from absorption at spectral type B2 into emission at earlier spectral types, a behaviour never reported before. The emission results from a non-LTE overpopulation of the upper levels of these transitions relative to the lower levels, facilitated by close collisional coupling of the former to the C III ground state, which is close to LTE in all the sample stars. For HR 3055 and HR 2928 C II $\lambda\lambda 6462$ and 6151 \AA are not considered in deriving the average $\varepsilon(C)$. See S96 for a discussion of the nature of the non-LTE effects of C II $\lambda\lambda 4267$ and $6578/82 \text{ \AA}$.

Non-LTE and LTE abundances for all individual lines are displayed as a function of W_λ in Fig. 5, showing excellent consistency in non-LTE. A slight degradation of the overall consistency is indicated for τ Sco (see below). Atmospheric parameters and averaged $\varepsilon(C)$ are also given.

4. DISCUSSION & RESULTS

We have investigated the sensitivity of the transitions to modifications of atmospheric and several atomic parameters qualitatively. The individual lines show a different behaviour: C II $\lambda\lambda 6151$ and 6462 \AA are very sensitive to changes of $\log g$, ξ and collisional and photoionization cross-sections, C II $\lambda 4267 \text{ \AA}$ is sensitive to photoionization, and all C II line strengths react sensitively on T_{eff} changes. As an example, exchanging our current photoionization data with the homogeneous set of N02a would result in considerably reduced uncertainties in the mean $\varepsilon(C)$ of τ Sco and HR 3055. However, for the same model configuration abundances from C II $\lambda 4267 \text{ \AA}$ in the other stars are reduced by up to 0.5 dex, approximately reproducing the LTE results in Fig. 5, while the remaining lines behave similarly to the final model. Further analyses have to be made to quantify these dependencies.

LTE analyses may produce abundances from the prominent C II $\lambda 4267 \text{ \AA}$ transition in error by ~ 0.3 – 0.8 dex, by up to ~ 0.4 dex in the case of C II $\lambda\lambda 6578/82 \text{ \AA}$ (note that \sim zero corrections may also occur), and by ~ 0.6 – 0.8 dex for the weak C II $\lambda\lambda 6151$ and 6462 \AA lines in the cooler stars. In the hotter stars the last two lines turn into emission and cannot be reproduced at all assuming LTE. All other transitions are subject to non-LTE corrections on the order of ~ 0 – 0.2 dex.

Noteworthy (small) discrepancies to the overall excellent agreement arise only for the C II $\lambda\lambda 4267$ and $6578/82 \text{ \AA}$ transitions in τ Sco. Among the sample stars τ Sco is the only object showing a considerable (clumped) stellar wind and hard X-ray emission (see Howk et al. 2000). The problems may be related to these complications, as wind emission affects the $H\alpha$ profile and the X-ray emission the photoionization rates, which both have to be modelled correctly in order to reproduce these strongly non-LTE affected C II lines accurately.

Our non-LTE computations reproduce the C II $\lambda 4267 \text{ \AA}$ theoretical equivalent widths of S96 (his Fig. 1).

For C II $\lambda\lambda 6578/82\text{ \AA}$ we reproduce the S96 values at 15 kK; however at 20 kK our W_λ are $\sim 10\%$ lower and at 30 kK up to 50% higher (see S96, Figs. 5 and 6). The difference arises because we use non-LTE populations when computing the H α line opacities which define the continuum against which these lines are measured (S96 assumes LTE). Note also that the T_{eff} -scale employed by S96 for his comparison with observation appears to produce values of T_{eff} lower by 700–3 000 K than our derivations.

A highly consistent mean $\varepsilon(\text{C}) = 8.29 \pm 0.03$ is derived from the sample stars, which provides a tight estimate to the present-day C abundance from young stars in the solar vicinity. The atmospheric composition appears to be unaffected by chemical mixing in the course of stellar evolution, i.e. we find no trend of $\varepsilon(\text{C})$ with evolutionary age. For comparison, adopting Kilian's (1992) results

one derives a mean $\varepsilon(\text{C}) = 8.19 \pm 0.12$ from the same six stars, implying a systematic shift and a significantly increased statistical scatter. More objects need to be further analyzed in order to verify the claim of such homogeneous present-day (slightly) sub-solar – considering as references $\varepsilon(\text{C})_\odot = 8.39 \pm 0.05$ (Asplund et al. 2005) or $\varepsilon(\text{C})_\odot = 8.52 \pm 0.06$ (Grevesse & Sauval 1998) – C abundances in nearby associations (HR 1861: Ori OB1; τ Sco, HR 5285: Sco-Cen) and in the field (the other stars).

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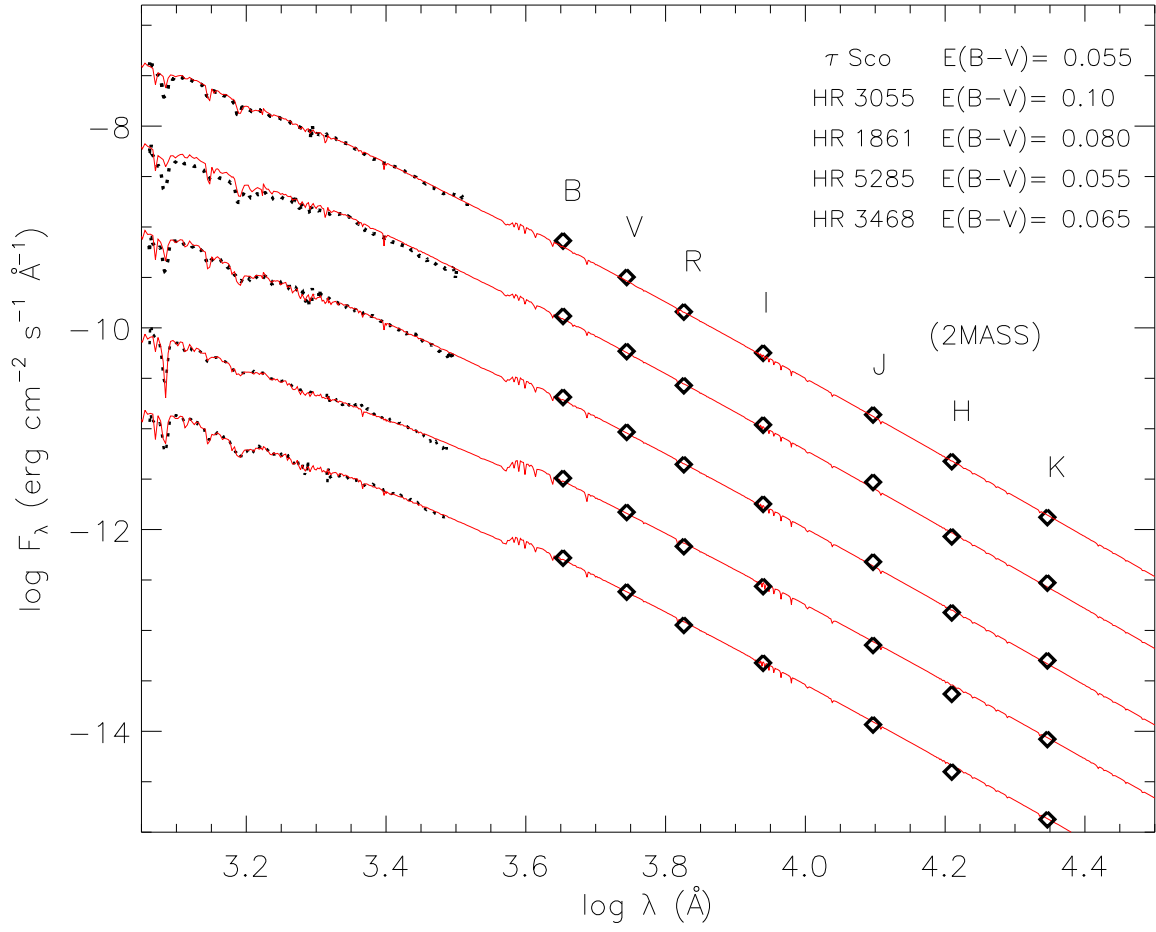


FIG. 1.— Best fits of theoretical energy distributions to measurements by IUE (dotted lines) and Johnson and near-IR 2MASS photometry (diamonds). The observed fluxes are dereddened by the values indicated using a standard reddening law and assuming $R_V = A_V/E(B-V) = 3.1$ as typical for the local ISM. They were degraded to the resolution of the ATLAS9 fluxes. The models are normalized to the observed V magnitudes and shifted for clarity relative to each other. See Fig. 5 for atmospheric parameters.

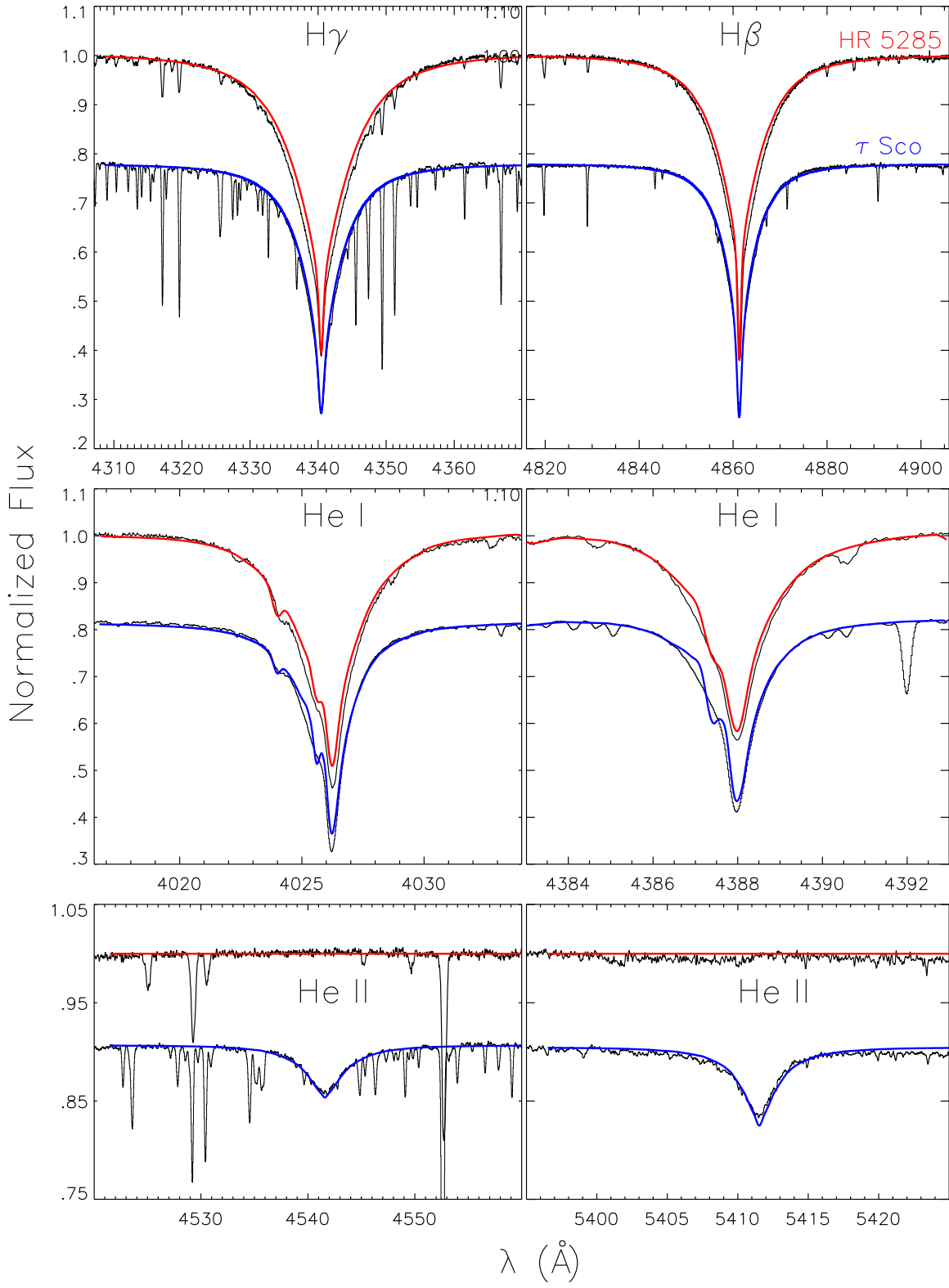


FIG. 2.— Comparison of synthetic H and He I/II lines (smooth lines) with observation of a B0 V (τ Sco) and a B2 V (HR 5285) star. Atmospheric parameters as summarized in Fig. 5 are employed.

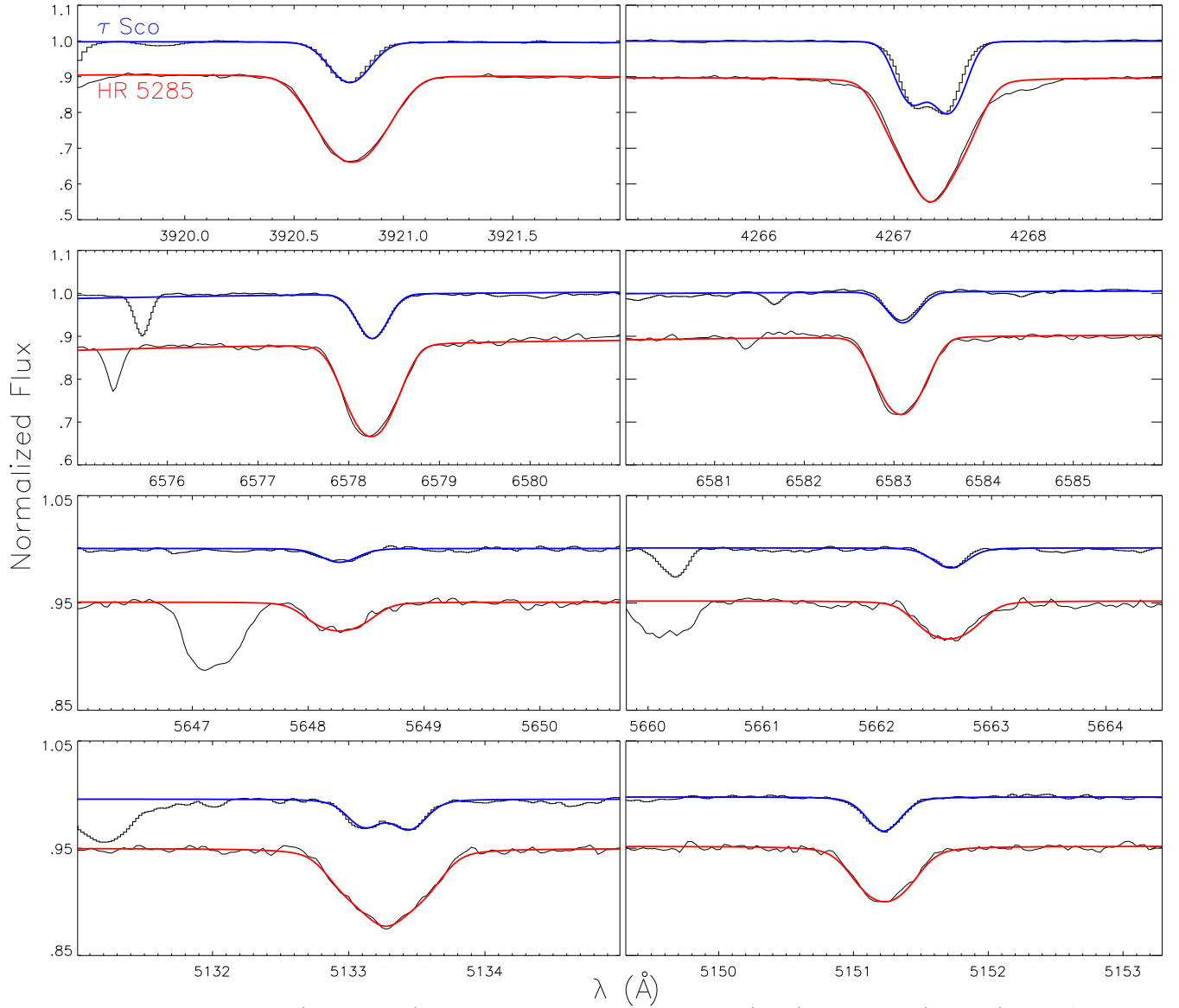


FIG. 3.— Examples of best fits (smooth lines) to observed C II features for a B0 V (τ Sco) and a B2 V (HR 5285) star. Atmospheric parameters and averaged $\varepsilon(\text{C})$ of each star are given in Fig. 5.

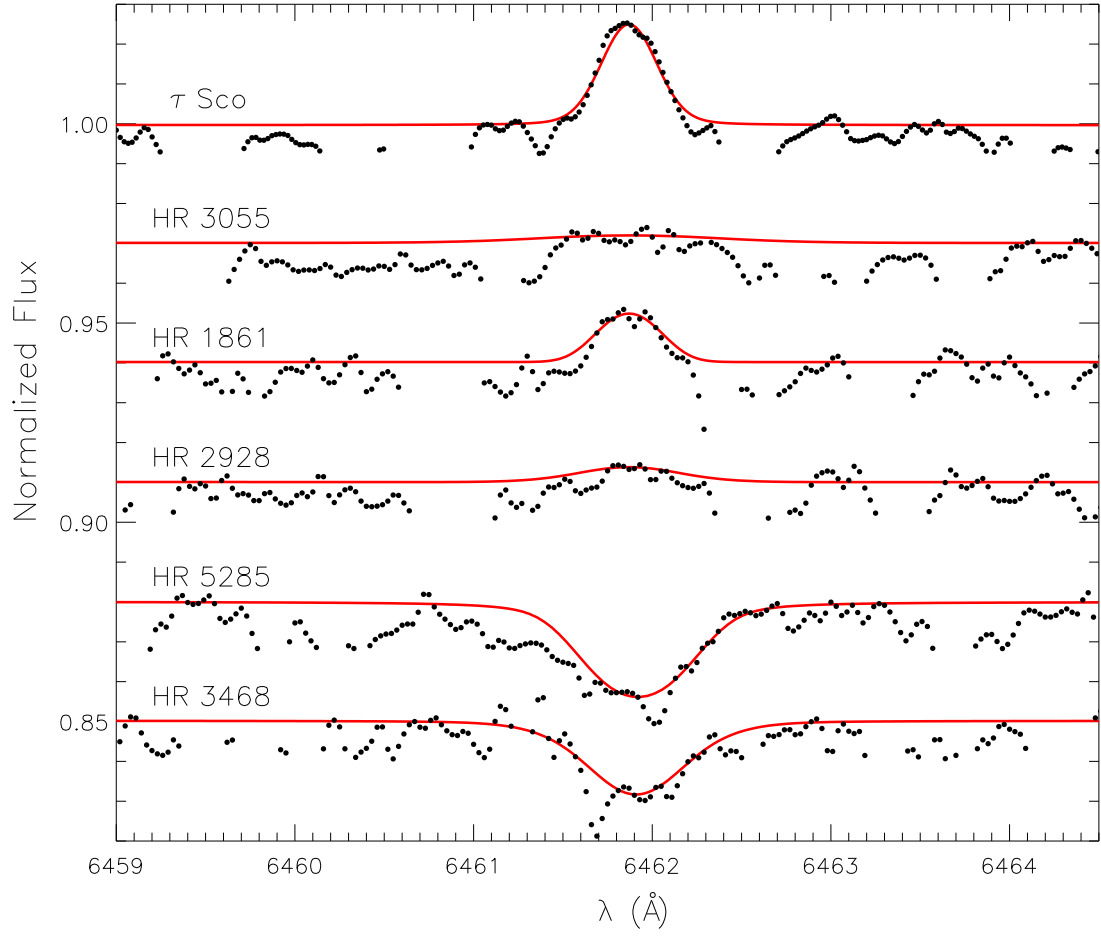


FIG. 4.— Best fits to the C II $\lambda 6462 \text{ \AA}$ line in the six sample stars. For clarity, the stronger telluric features in this spectral region are suppressed in the observed spectra (dots).

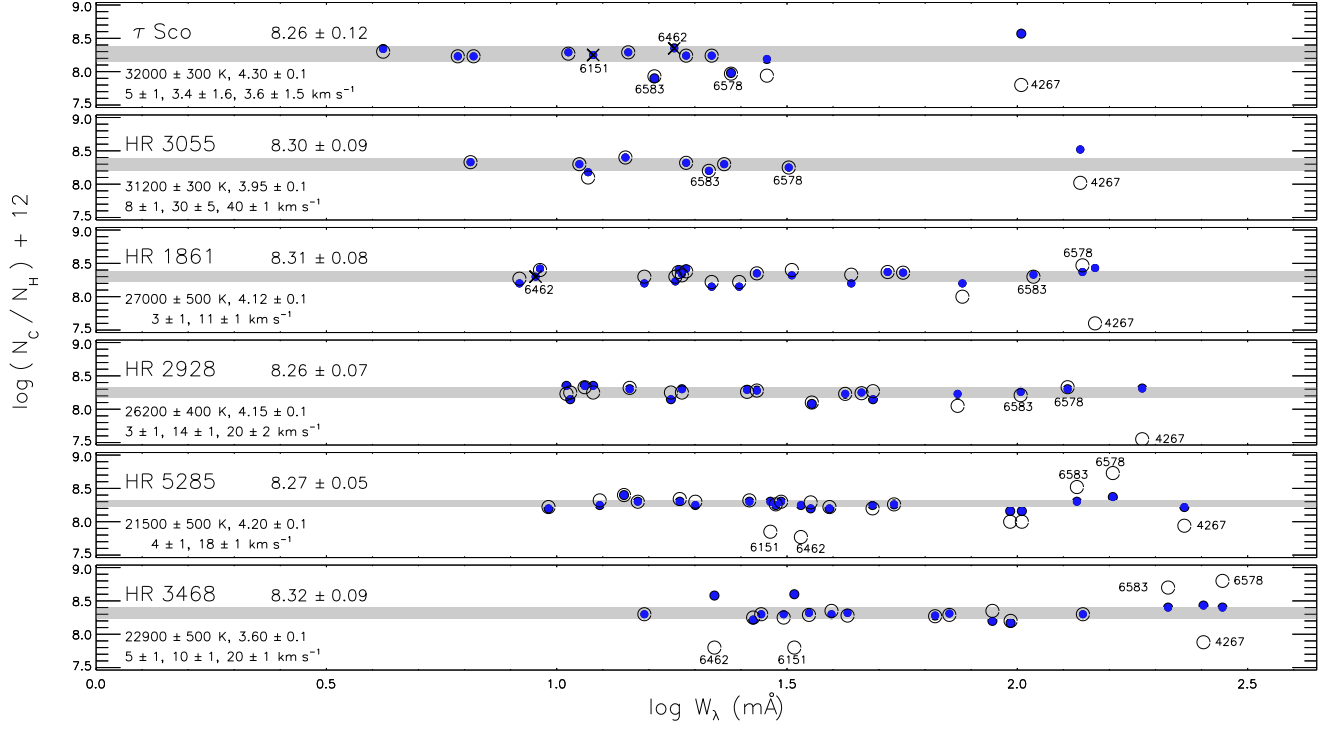


FIG. 5.— Non-LTE (filled circles) and LTE (open circles) abundances vs. equivalent width for all the lines that could be measured in each spectrum (a linelist is provided in the text). In the upper left part of each row an identification of the star and its carbon abundance is given. In the lower left part T_{eff} , $\log g$, microturbulence, $v \sin i$ and macroturbulence (where non-zero) are shown. For abundances and velocities statistical 1σ -uncertainties are provided and for T_{eff} and $\log g$ the errors from our derivation are presented. The grey rectangles correspond to 1σ -uncertainties of $\varepsilon(C)$. Identification of lines with high sensitivity to non-LTE effects is displayed. Emission lines are marked by crosses (C II $\lambda\lambda 6151$ and 6462 \AA in τ Sco and $\lambda 6462 \text{ \AA}$ in HR 1861): LTE calculations are not able to reproduce them.